Mirror Matter, the cosmological Lithium Problem and Dark Matter

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The abundance of lithium-7 confronts cosmology with a long lasting problem between the predictions of standard Big Bang Nucleosynthesis and the baryonic density determined from the Cosmic Microwave Background observations. We investigated the influence of the existence of a mirror world, focusing on models in which miror neutrons can oscillate into ordinary neutrons. Such a mechanism allows for an effective late time neutron injection, which induces an increase of the destruction of beryllium-7 but for mirror baryonic densities much lower than $\Omega_{\rm DM}$.

1 Introduction

The abundances of the light elements produced during the primordial nucleosynthesis (BBN) in the early hot phase of the Universe is one of the historical pillar of the big-bang model. When using for the baryon over photon number ratio (η), the value determined by the cosmic microwave observations, the BBN predictions for ^{4}He, D and ^{3}He are in very good agreement with those deduced from observations. However, there remains, a yet unexplained, discrepancy of a factor $\approx$3, between the calculated and observed ^{7}Li abundances [1, 2], that has not been reduced, neither by recent nuclear physics experiments, nor by new observations. One of the solutions to this problem would be to inject neutrons during the late stages of BBN [3]: that would increase ^{7}Be destruction (the BBN progenitor of ^{7}Li), due to a more efficient neutron capture, leading to a lower ^{7}Li final abundance. Injecting neutrons is indeed not something easily performed without including physics beyond the standard model of particle physics. Such an idea can be realized by introducing a mirror sector, constructed by assuming that the gauge group G of the matter sector is doubled to the product $G \times G'$. The Lagrangian of the two sectors, ordinary and mirror, are identical so that they have the same particles content such that ordinary (resp. mirror, noted with a prime) matter fields belonging to G (resp. G') are singlets of G' (resp. G). They also have the same fundamental constants so that the microphysics (and in particular the nuclear sector) is identical. However, the temperature evolutions and the baryonic densities can be different in both worlds [4]. In particular, if the temperatures in both worlds were identical, then the effect of the mirror world would be equivalent to an effective number of neutrino families, $\delta N_{\rm eff} = 6.14$, too large a number to be compatible with observations.

Such a sector was initially proposed by Li and Yang [5] in an attempt to restore global parity symmetry and was then widely investigated [4] (see also Refs. in [6]). As shown in Ref. [7], any *neutral* ordinary particle, fundamental or composite, can be coupled to its mirror partner hence leading to the possibility of, back and forth, oscillation between ordinary and mirror particles, in particular between neutrons (n) and mirror neutrons (n'). This has motivated experimental searches for nn'-oscillations which provided the constraint on the oscillation time scale: $\tau_{\rm osc} > 448\,$s (90% C.L) [8]. From a cosmological point of view, mirror particles have been advocated as a dark matter candidate (see e.g. Ref. [9]). In particular, mirror baryons do not interact with photons and have the same mass as ordinary baryons. From our world they can thus be considered as stable, self-interacting dark matter particles.

2 Model

The Friedmann equation contains both the ordinary and mirror matter and is dominated by the radiation energy density during BBN. The additional term corresponding to the contribution of the mirror sector is calculated as in the ordinary sector, including all relativistic particles, but with a difference in the temperature evolutions. The BBN computations depend on 4 parameters. The standard parameter is the number of ordinary baryons per photon (η) given by the CMB analysis [10, 11]. It has to be complemented by its mirror counterpart (η'), the ratio $x \equiv T'/T$ of mirror/ordinary photon temperatures (a constant except during the electron–positron annihilation period), and the the oscillation time scale ($\tau_{\rm osc}$). Since the physics in the two sectors is identical, the reaction rates are the same in both worlds and are those used in our previous BBN works [1]. However, BBN is different because of the different temperatures and baryonic densities. The network includes 16 isotopes and 27 reactions. These are the usual 8 isotopes and their mirror partners, the 13 main BBN reactions and their mirror counterparts plus the $n \leftrightarrow n'$ oscillation term. None of the previous investigations on mirror BBN [12] have considered the effect of neutron oscillations between the two worlds so that in this first study we use a few approximations. We assume that, during free mirror neutron decay, the mirror neutron abundance evolves as in vacuum, i.e. as $e^{-t/\tau}\cos^2(t/\tau_{\rm osc})$ [13], with τ the usual neutron beta-decay lifetime, i.e. that n' decay to n at a rate of $\lambda_{\rm n'\to n} = \frac{2}{\tau_{\rm osc}}\tan\left(\frac{t}{\tau_{\rm osc}}\right)$. In standard BBN, the weak interaction maintains the thermal equilibrium between neutrons and protons until their rates become slower than the Hubble expansion rate at a typical temperature of $T \approx 3.3$ GK. This freeze-out of the weak interaction is followed by neutron free decay until $T \approx 0.9$ GK when nucleosynthesis begins. This is during this phase of free decay that we assume that neutron oscillation occurs between the two worlds. We neglect $\lambda_{\rm n\to n'}$ inverse process because with our choice of parameters, relevant to the ^{7}Li problem, when the n abundance is initially dominant $\lambda_{\rm n\to n'}$ is suppressed by the factor $\tan(t/\tau_{\rm osc})$. Later, when this factor is no longer negligible, it is the n abundance that becomes negligible. In a subsequent study, we will consider the effect of interactions of mirror neutrons with other mirror/ordinary particles that could modify the $n \leftrightarrow n'$ oscillation rate.

3 Results

For a wide range of parameters, we obtain a reduction of the ^{7}Be+^{7}Li final abundance compatible with observations (at the expense of a moderate D overproduction) providing a possible

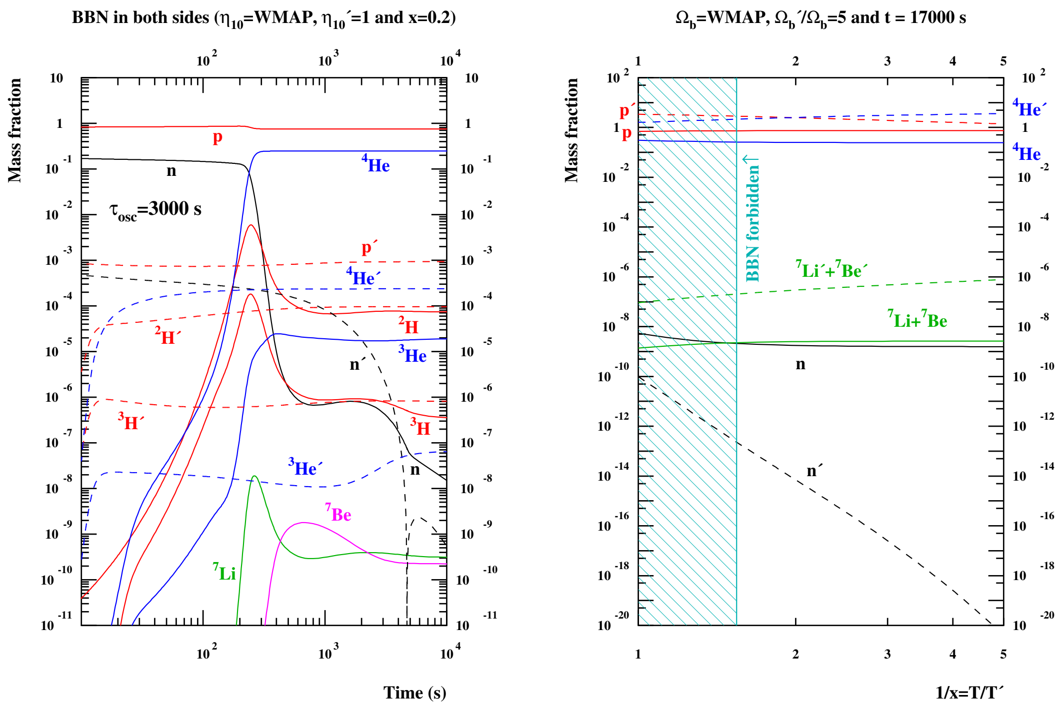

Figure 1: Left panel: abundances (mass fractions) in the ordinary (solid lines) and mirror (dashed lines) worlds as a function of time in the presence of $n' \leftrightarrow n$ oscillations. Right panel: final mass fractions as a function of T/T' (without oscillations) assuming $\Omega'_{\rm b} = \Omega_{\rm DM}$.

solution to the lithium problem [6]. Figure 1 (left) shows the result of a BBN calculation in both worlds with typical values of the parameters: $\eta = \eta_{\rm WMAP}$ [10], $\eta' = 10^{-10}$, $x = 0.2$ and $\tau_{\rm osc} = 3 \times 10^3$ s. (Mirror isotopes up to ^{4}He' are displayed for completeness but are not needed for the discussion.) Initially, because of the difference in baryonic densities, the neutron abundance is much higher in our world but, during standard BBN the neutron abundance decreases very rapidly compared to mirror BBN because of the higher temperature and density. It can be seen that after a time of order 300 s, the abundance of the mirror neutrons, n', is much higher than the normal neutron abundance. This is due to the fact that, for this choice of parameters (T' and $\rho'_{\rm b}$), mirror BBN is limited to n' decay while normal BBN is in its full development. Then, when the n abundance dropped below the n' one, n injection from oscillating n', at the time of ^{7}Be formation, leads to its destruction due to a more efficient neutron capture. On the contrary, the abundance of D increases: we obtain a reduction of the ^{7}Li + ^{7}Be abundance at the expense of a moderate higher deuterium abundance.

Obviously, it would be desirable to both solve the lithium problem and provide a candidate for dark matter with the observed density i.e. $\Omega'_{\rm b}/\Omega_{\rm b} \approx 5$ [10, 11]. Unfortunately, this is not the case as shown in Fig. 1 (right), corresponding to BBN final abundances as a function of x, assuming this ratio of baryonic densities. The hatched area on the left is excluded by BBN as for $T'/T \equiv x \gtrsim 0.6$ the increase in the effective number of neutrino families, $\delta N_{\rm eff} \approx 7x^4$ exceeds the limits provided by ^{4}He observations. Within the x allowed range, the mirror neutron abundance is smaller than its ordinary counterpart by several orders of magnitude. This is easily explained by the higher mirror baryonic density that makes nucleosynthesis more efficient in the mirror sector than in the ordinary one. Neutron oscillations were switched off in these calculations, but it is obvious that they cannot provide a sufficient ordinary neutron source to significantly affect ^{7}Be production. Note that for $x \lesssim 0.5$, ^{4}He' is more abundant than p' (H') resulting in exotic stellar evolutions.

4 Conclusions

We investigated the possibility of a mirror sector in which mirror-ordinary neutrons oscillations could provide a solution to the primordial lithium problem We have shown [6] that as soon as $x \lesssim 0.6$ the helium-4 abundance is in agreement with the observations while the agreement for both the deuterium and helium-4 abundances can be obtained within a large domain of the parameter space. Unfortunately, the observed dark matter density is outside of this domain. Besides, being self-interacting and dissipative, mirror matter is not a good dark matter candidate.

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